ANALOG OPTICAL SIGNAL PROCESSING FOR WIDEBAND RADARS AND ELECTRONIC SUPPORT MEASURES SYSTEMS

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AMNON YARIV**
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AOSP KICKOFF MEETING
AUG. 7-8, 2002

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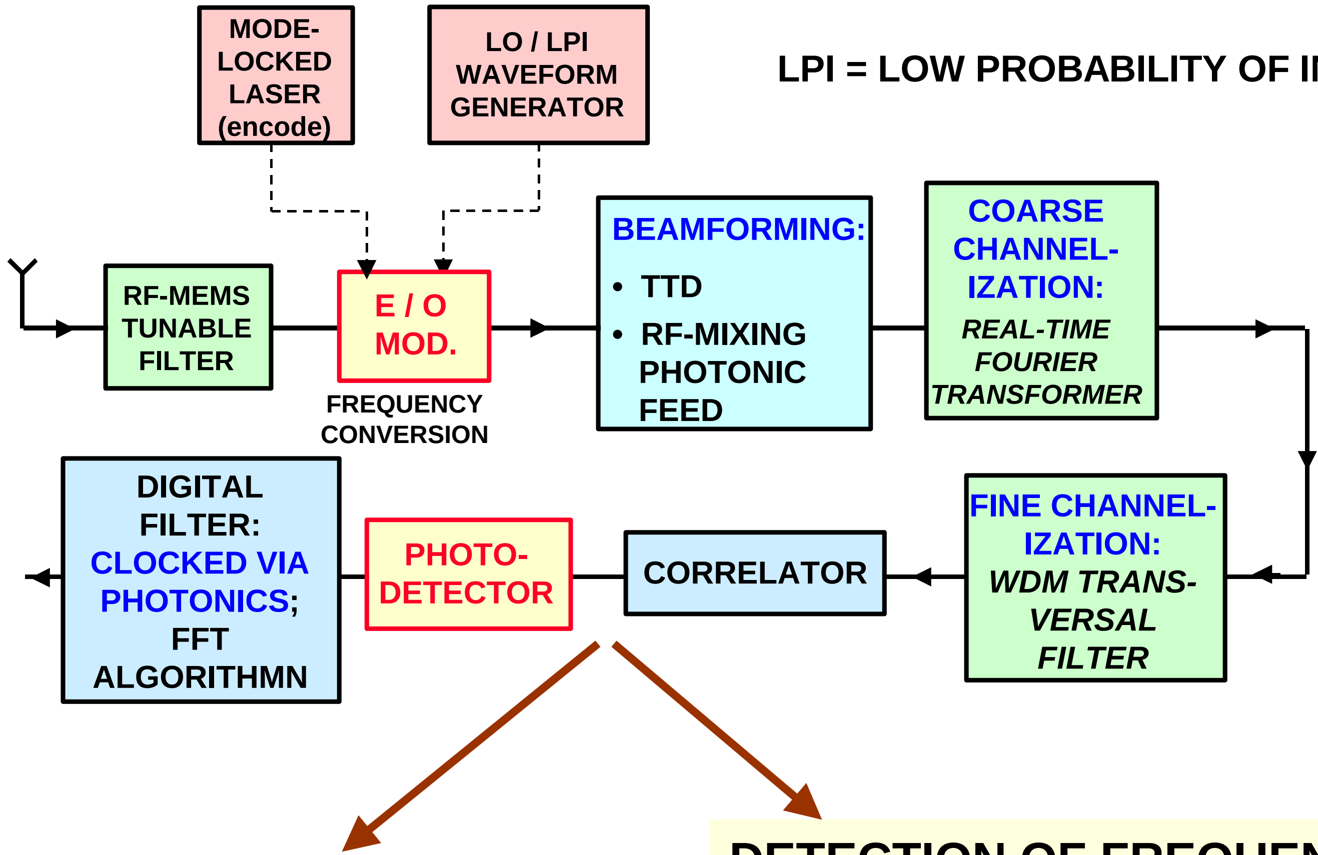
•• CALIFORNIA INSTITUE OF TECHNOLOGY, PASADENA, CALIF.

OUTLINE

- INTRODUCTION AND PROGRAM GOALS
    - HRL TEAM ORGANIZATION
- PROPOSED ANALOG OPTICAL SIGNAL PROCESSING FOR APPLICATIONS IN LOW PROBABILITY OF INTERCEPT (LPI) RADAR AND ELECTRONIC SUPPORT MEASURES (ESM) SYSTEMS:
    - PULSE COMPRESSION FOR MULTI-LINE WAVEFORM GENERATED BY PHOTONIC OSCILLATOR
    - TRANSVERSAL FILTERS FOR ESM PULSE DETECTION
    - ADVANCED PHOTONIC COMPONENTS BASED ON PHOTONIC BANDGAP (PBG) DESIGNS AND HIGH-Q GLASS-BASED MICRO-RESONATOR FILTERS

ANALOG OPTICAL PROCESSING OF RF-PHOTONIC SIGNALS: COMPRESSION AND DETECTION OF LPI WAVEFORMS

LPI = LOW PROBABILITY OF INTERCEPT



COMPRESSION (FM/PHASE-ENCODING) OF PHOTONIC LPI MULTILINE WAVEFORMS => RANGE RES. OF < 1 ft (τ_{comp} ~ 2 nsec)

DETECTION OF FREQUENCY-SPREADED LPI WAVEFORMS FOR ELECTRONIC SUPPORT MEASURES (ESM) => CHANNELIZATION OF RF-PHOTONIC SIGNALS VIA WDM-BASED OPTICAL FILTERS

HRL AOSP PROGRAM ORGANIZATION

- **Program Monitored by AFRL/WPAFB and DARPA-MTO**

CALTECH:

Prof. A. Yariv
Prof. K. Vahala
Prof. A. Scherer

- Photonic Bandgap (PBG) Device
- Micro-Sphere Resonators

RAYTHEON COMPANY:

- **Dr. R. Buckley (Surveillance and Reconnaissance Segment, El Segundo, Calif.)**

System Analysis for LPI Radar, especially Photonic Waveform Gen.

- **Dr. J. Allen (C³I, Garland, Texas)**

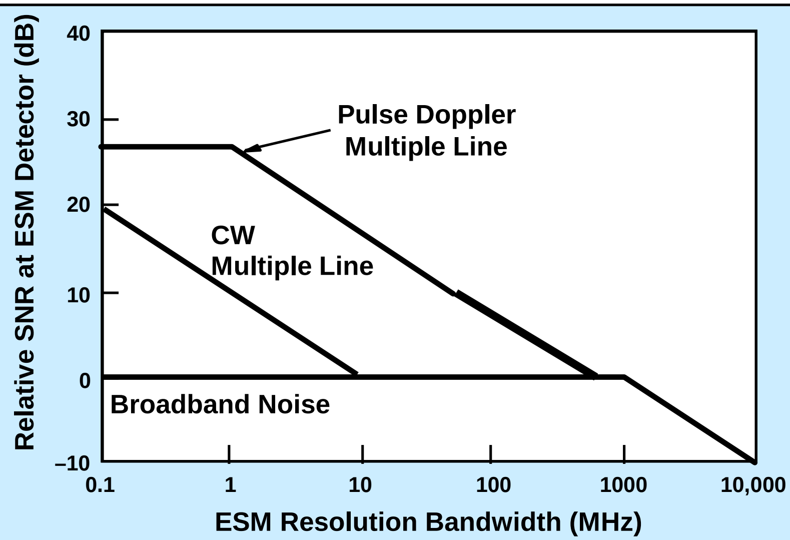
Pulse Detection for ESM EW System

HRL LABORATORIES

Communication and Photonics Lab.
W. Ng, D. Yap, R. Hayes, A. Walston, K. Sayyah

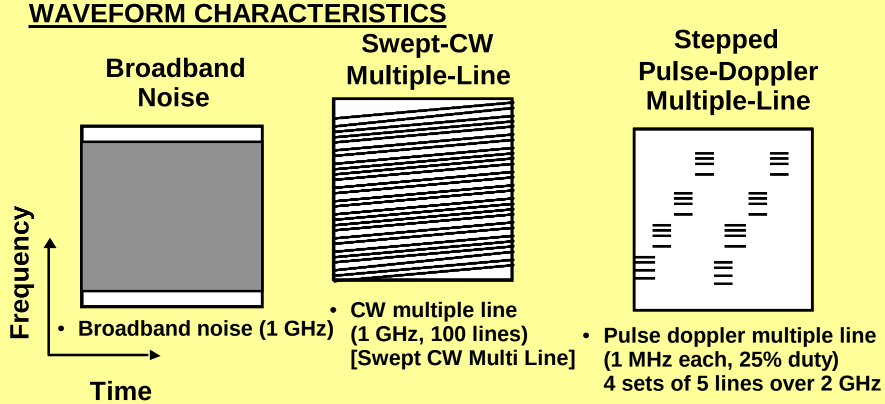
RF-Photonic Devices/Subsystems: Including Photonic Encoders & Transversal Filters

FREQUENCY-SPREADED WAVEFORMS FOR REDUCED PROBABILITY OF INTERCEPTION

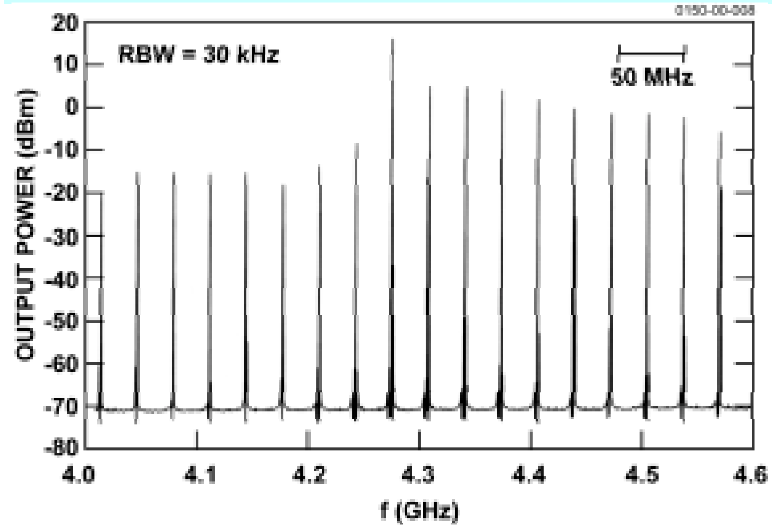


Note: 1) Equal radar detection performance
2) Uniform noise background / uniform target reflection
3) Waveform time equal (equal time spread)

WAVEFORM CHARACTERISTICS



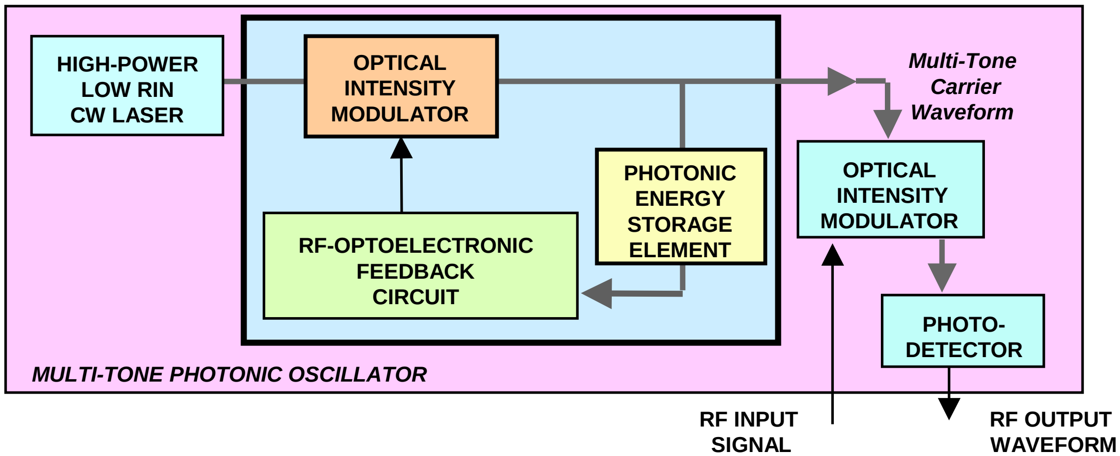
Measured RF Spectrum of Multiline Photonic Oscillator:



- Reduced Probability of Interception
- Ultra-Wideband Carrier Permits Use of Reduced Transmit Power Levels
- Line Spacing and Bandwidth Depends on Anticipated Performance of ESM Receiver

→ *Pulse Compression in Analog Optical Signal Processing (AOSP) Program*

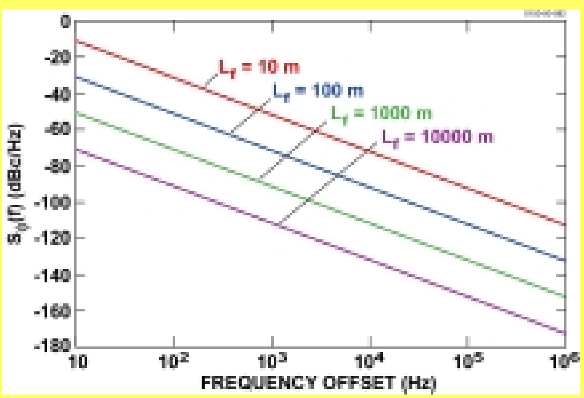
FREQUENCY-SPREAD CARRIER WAVEFORM GENERATION



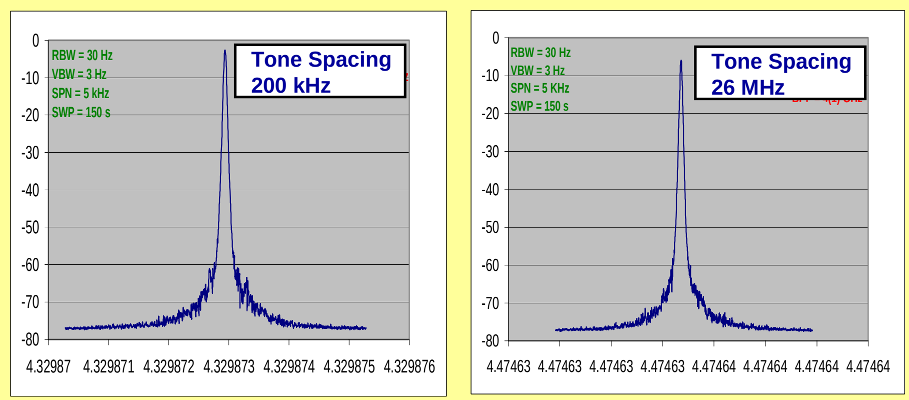
- Phase Noise Inversely Related to Square of Storage Time
- Tone Spacing is Inversely Related to Storage Time
- Dual Loop Approach Achieves Larger Tone Spacing As Well As Low Phase Noise

LPI, AGILE WAVEFORM GENERATION, PULSE COMPRESSION

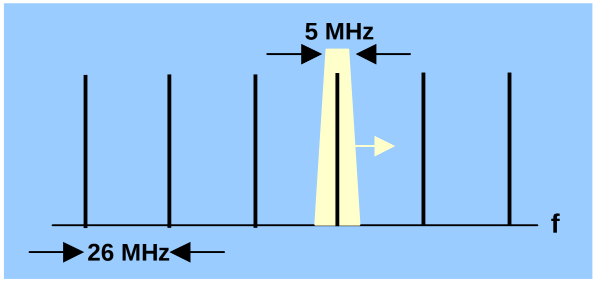
PREDICTED PERFORMANCE

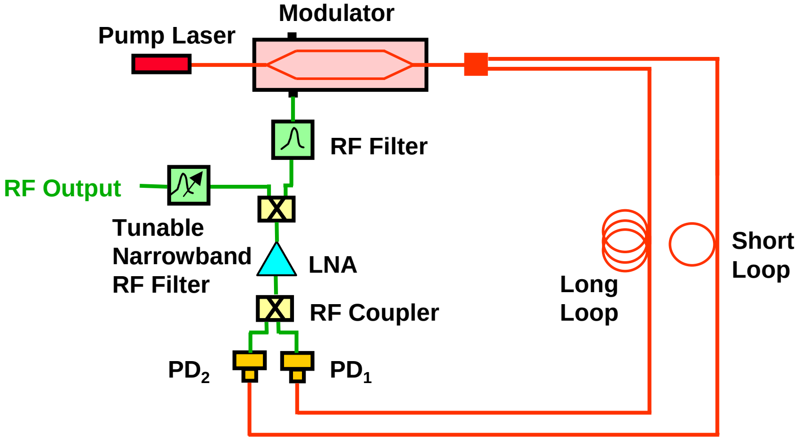


MEASURED PERFORMANCE

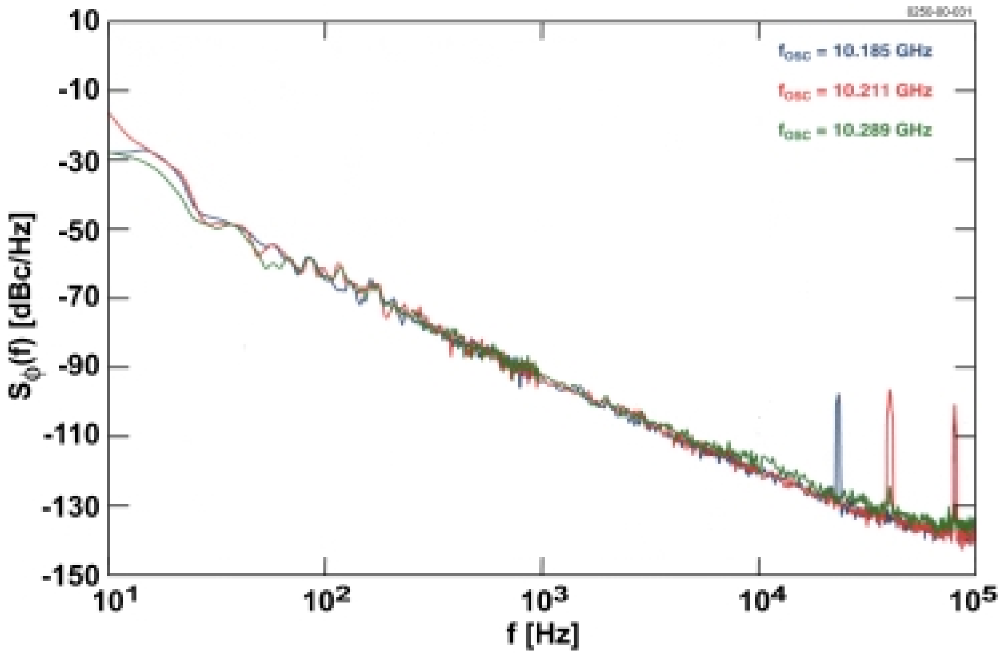


Multi-tone Photonic Oscillator Phase Noise



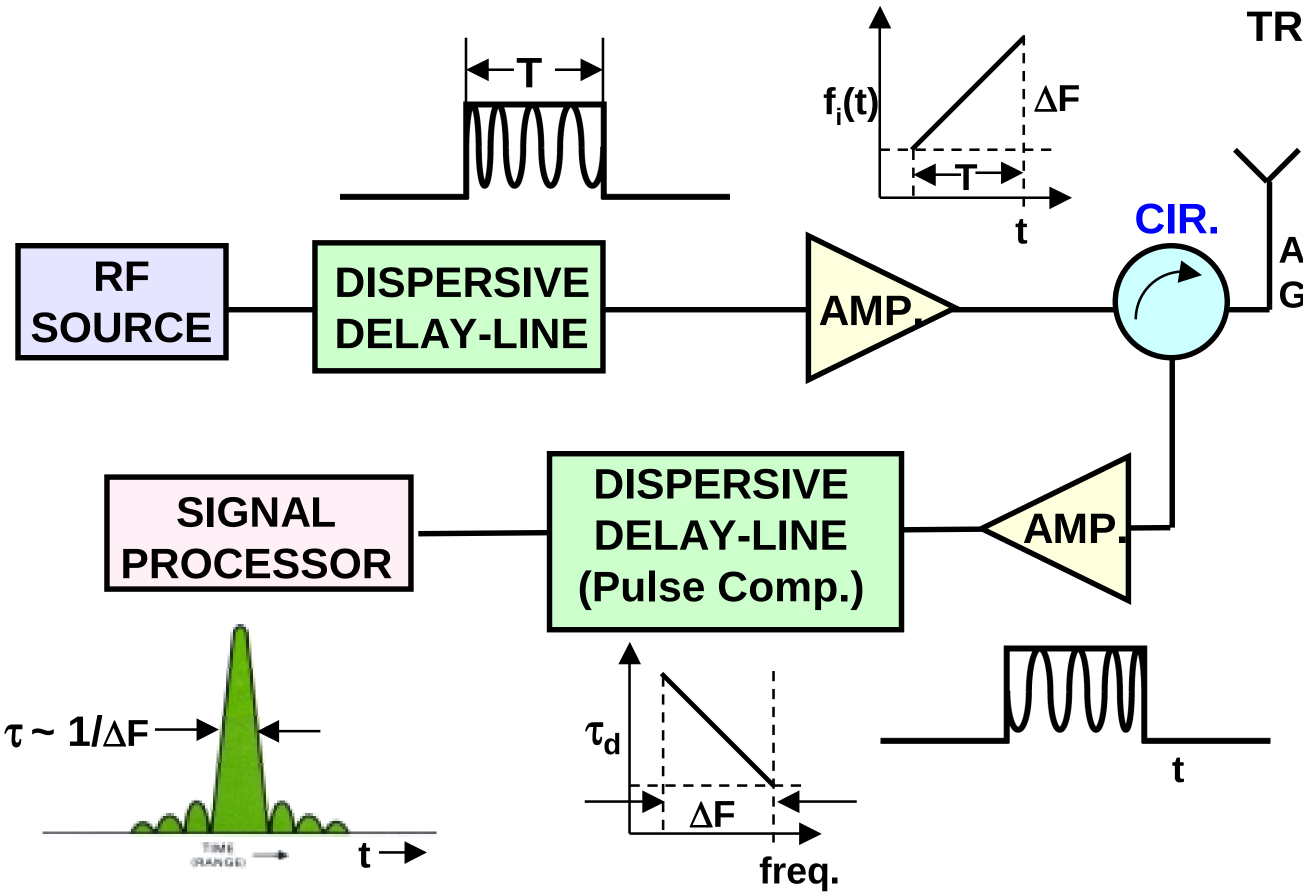


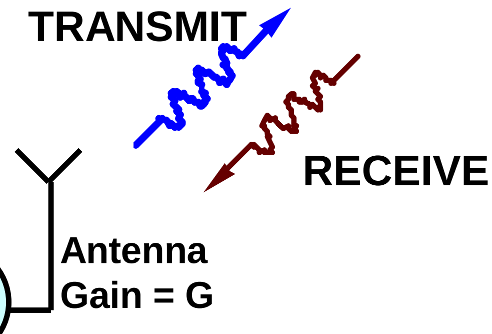
Dual-Loop Multi-tone Photonic Oscillator



- **Dual-Loop Multi-Tone Photonic Oscillator with 1 km Long Loop and <10 m Short Loop**
- **Tunable Narrowband Filter (< 5 MHz 3dB-BW) At Photonic Oscillator Output To Select Tone**
- **Nearly Identical Measured Phase Noise For Various Tones Separated By Multiples of 26 MHz**
- **Similar Phase Noise Measured between Single Tone and Multi-Tone Photonic Oscillator**
- **Injection locking => Phase-coherent Operation**

PULSE COMPRESSION: FM CHIRP





***RF-PHOTONIC LPI WAVEFORM* WILL BE:**

- **PHOTODETECTED AT ANTENNA BEFORE TRANSMIT**
- **PICKED UP BY REMOTED OPT. MODULATOR ON RECEIVE**

FROM RADAR RANGE EQUATION:

$$P_{received} \propto \frac{G(P_{AV})}{R^4} \propto T(PRF)P_{peak}$$

RANGE RESOLUTION (ΔR):

$$\Delta R = \frac{1}{2}cT \xrightarrow[\text{COMPRESSION}]{\text{PULSE}} \Delta R = \frac{1}{2}c\tau$$

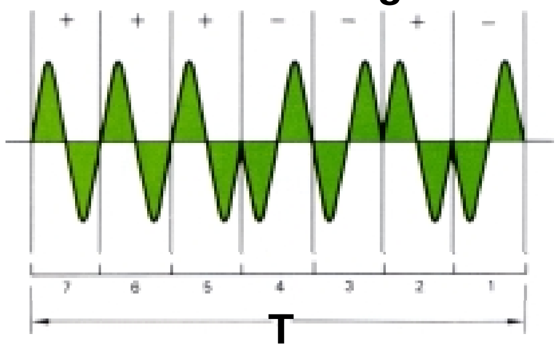
$$\text{Pulse Compression Ratio} = \text{PCR} = \frac{T}{\tau}$$

e.g. T ~ 1-100 μsec; ΔR ~ 1 ft for τ ~ 2 nsec

PULSE COMPRESSION: PHASE-CODING

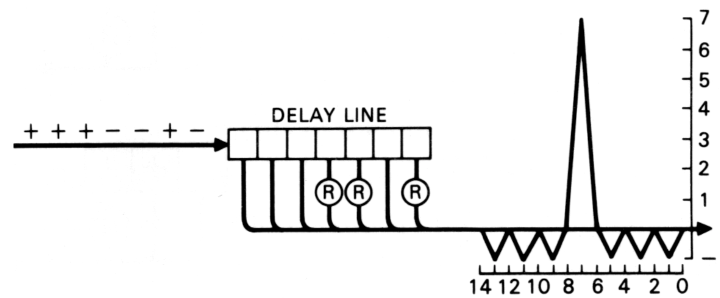
BINARY-PHASE CODED PULSE:

- Barker Code of Length N = 7



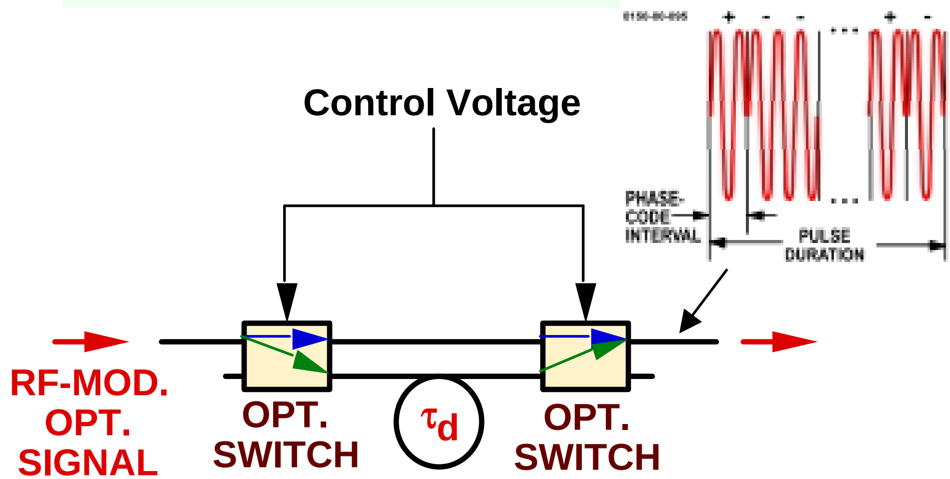
BINARY-PHASE DECODER FOR PULSE COMP. :

- For Barker Codes, PSL = -20log(N)



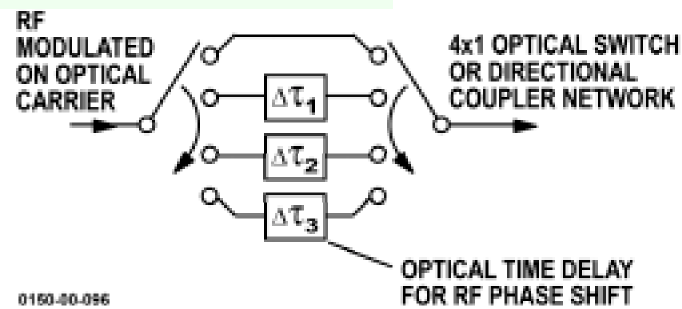
PHASE-CODING (BINARY, POLYPHASE) OF RF MODULATED ON OPTICAL CARRIER:

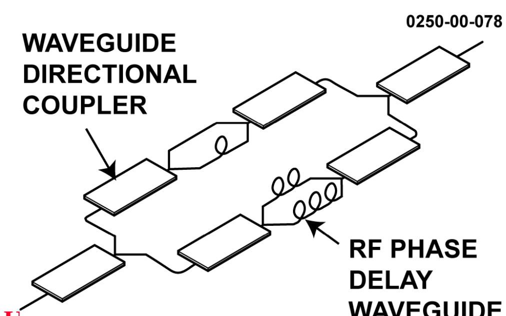
BINARY PHASE CODING:



- Switching Speed is determined by Code Interval (T_{code}):
  e.g. T_{code} = 100 nsec => 10 MHz switching

POLYPHASE CODING:





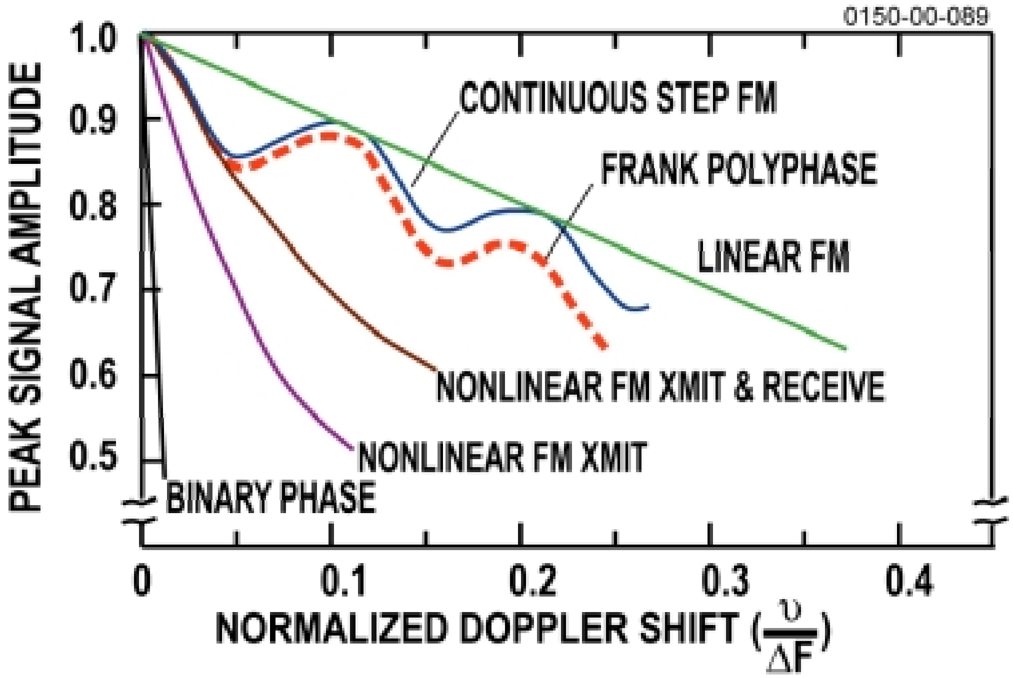
HRL LABORATORIES

PULSE COMPRESSION: FM CHIRP vs PHASE ENCODING

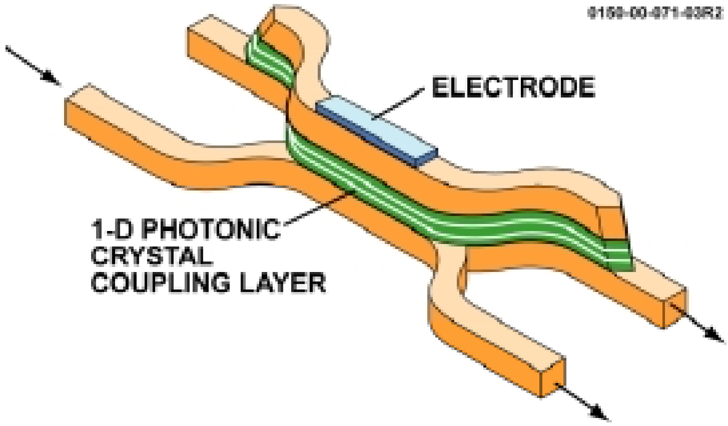
Raytheon

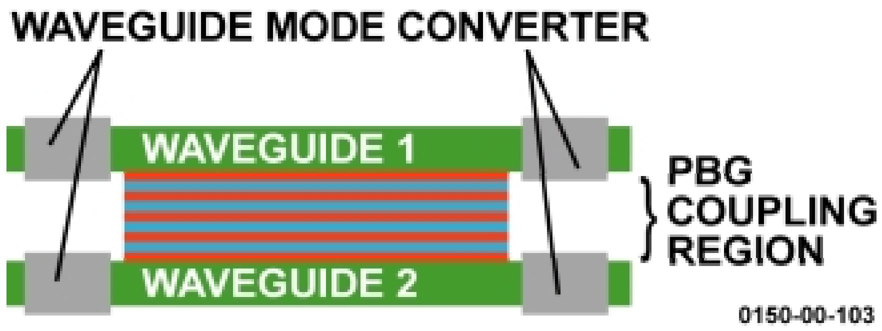
- **Analysis of Ambiguity Function (Range vs Doppler Shift)**
- **Considerations of Doppler Tolerance, Reconfigurability, Electromagnetic Compatibility (in a frequency band)**
- **Binary/Polyphase Codes, Complementary Codes, Peak Side Lobe (PSL), Integrated Side Lobe (ISL).**
- **Approaches to implement Phase Encoding/Decoding and FM-Chirp for an LPI Waveform, generated by the HRL/Raytheon Multi-line Waveform Generator.**

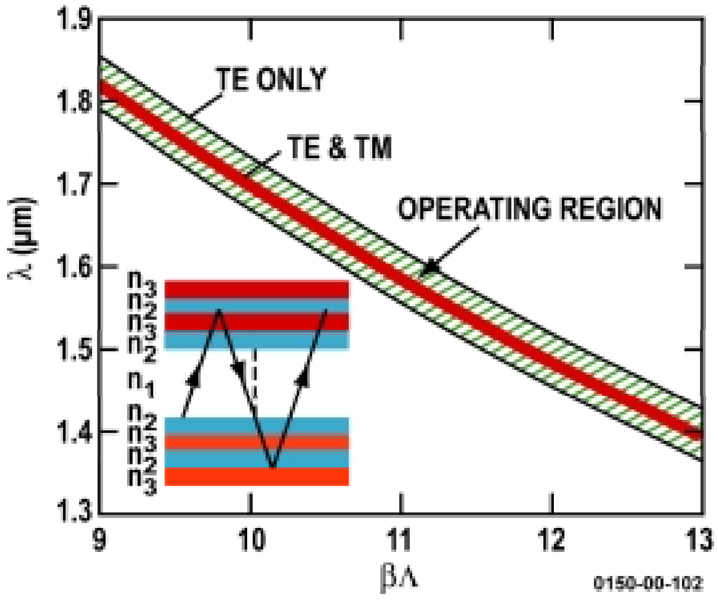
PLOT OF SIGNAL AMPLITUDE FROM RECEIVER vs NORMALIZED DOPPLER SHIFT FOR DIFFERENT WAVEFORMS:



DIRECTIONAL COUPLER SWITCH BASED ON 1-D PHOTONIC BANDGAP STRUCTURES





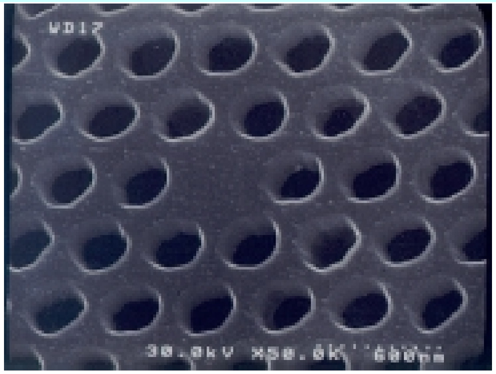


- TAKE ADVANTAGE OF DIFFERENT TUNNELING PROPERTIES OF TE AND TM MODES THROUGH THE 1-D PBG
- EXTINCTION RATIO > 25 dB, COUPLING LENGTH ~ 200 μm (1/6 that of Conventional Directional Couplers)
- ESTIMATED DEVICE SWITCH VOLTAGE ~ 4 V

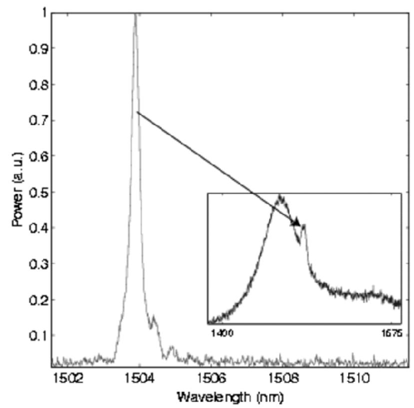
→ MORE APPLICATIONS OF PBG AS PROGRAM EVOLVES

WORK IN PHOTONIC BANDGAP DEVICES IN A. YARIV'S GROUP AT CALTECH

PBG DEFECT CAVITY LASER:



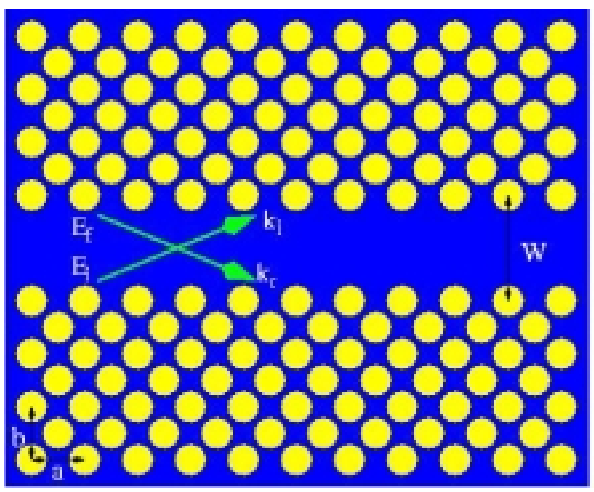
LASING SPECTRUM

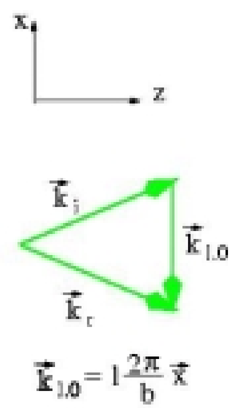


- **First reported* photonic defect cavity laser based on the PBG concept.**

* Science vol 284 (5421), pp. 1819-1821, 1999.

PBG WAVEGUIDE DESIGN:

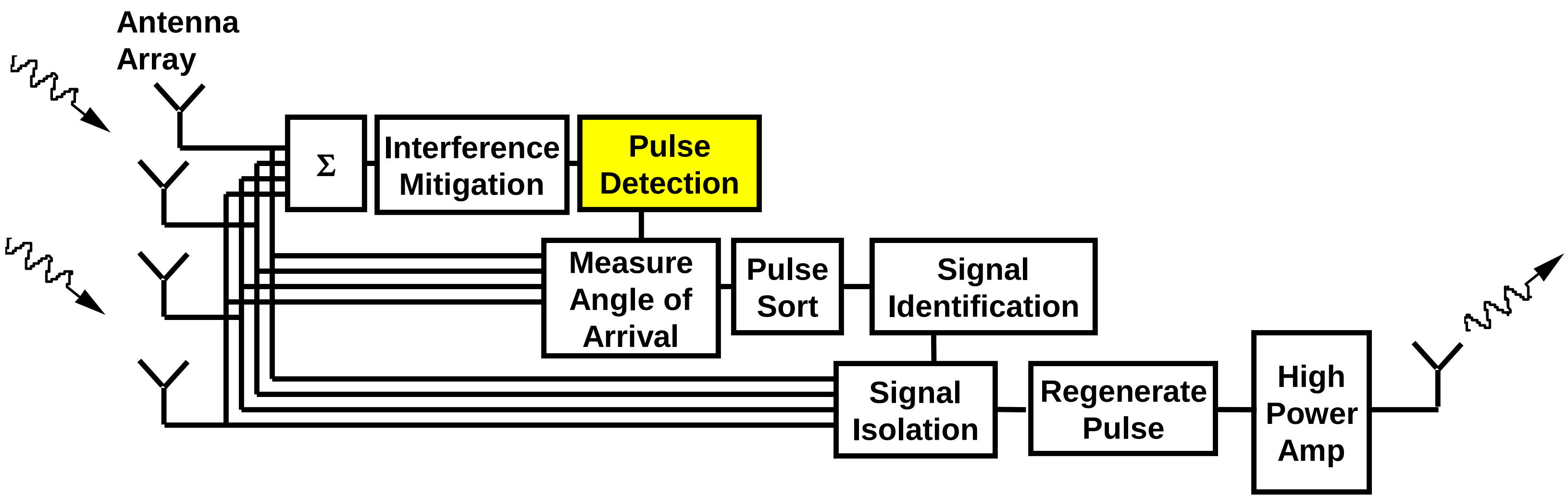




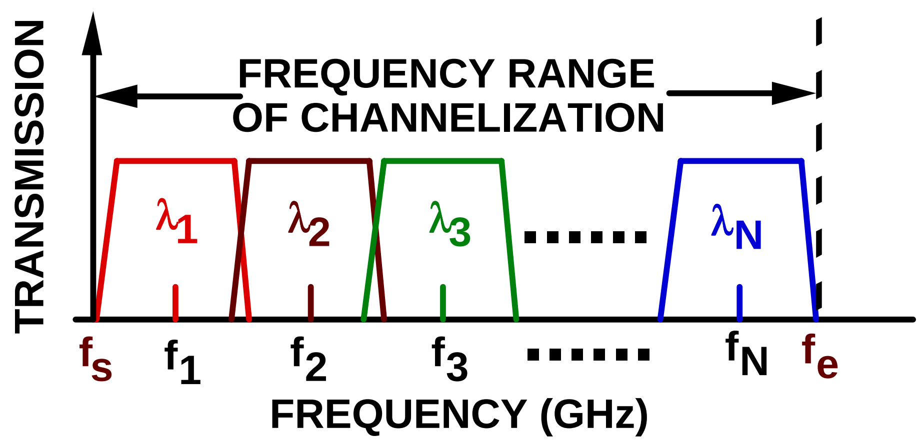
- **First analytical solution** for photonic crystal waveguides.**
- **Predicts, for the 1st time that low-loss guiding only occurs at Quantized Waveguide Width of W = b/4, 3b/4, 5b/4...**

** Opt. Lett., Vol 27, issue 11, page 936-938, June 2002.

SCHEMATIC OF ELECTRONIC WARFARE JAMMER:

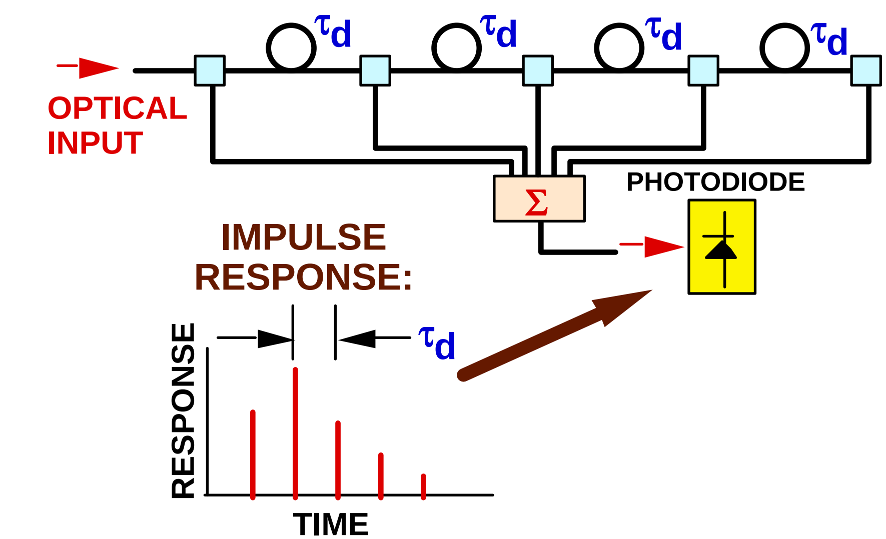


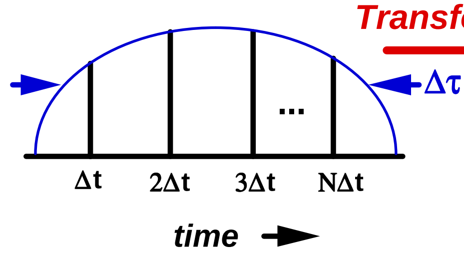
- **WDM-BASED TRANSVERSAL FILTERS CHANNELIZE FREQ. RANGE OF INTEREST FOR PULSE DETECTION, AND SUBSEQUENT DIGITAL SIGNAL PROCESSING (DSP).**

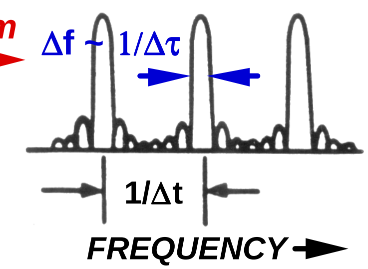


FINITE IMPULSE RESPONSE (FIR) RF-PHOTONIC FILTERS FOR MICROWAVE SYSTEMS

SINGLE POLARITY FIR FILTER FORMED FROM TAPPED DELAY-LINES:

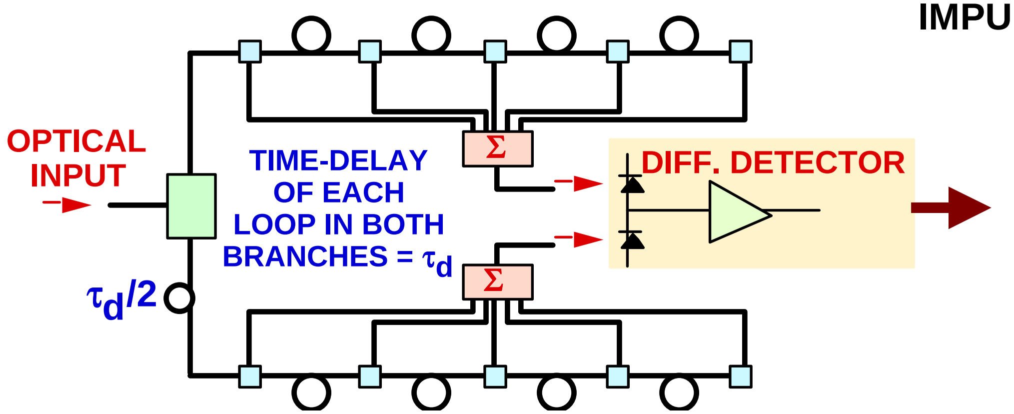


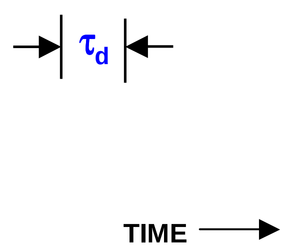


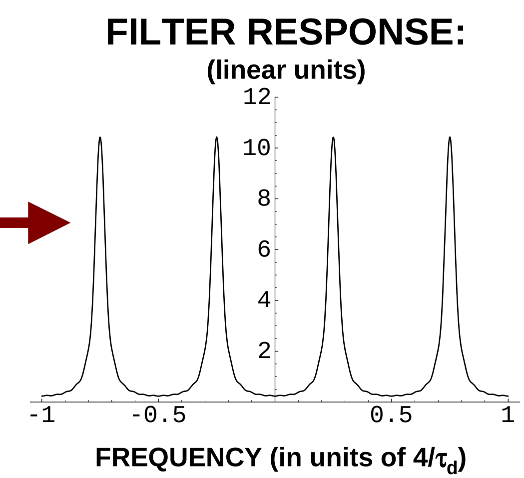


- FREQUENCY SPACING IS $1/\Delta t$
- FILTER Q ($=f_c/\Delta f$) INCREASES WITH INCREASES WITH THE NUMBER OF TAPS.

BIPOLAR FIR FILTER FORMED FROM TAPPED DELAY-LINES:

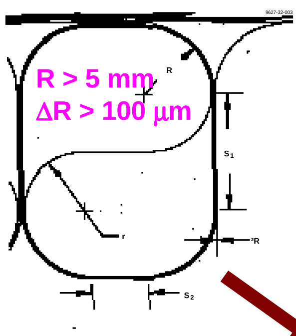




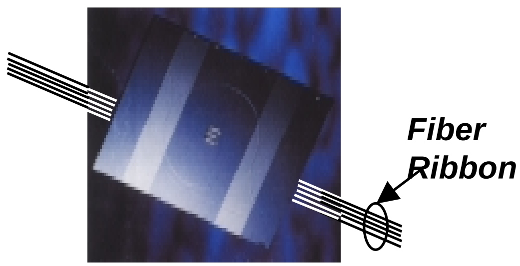


RF-PHOTONIC TAPPED DELAY-LINE FILTER FORMED FROM SILICA WAVEGUIDE CHIP

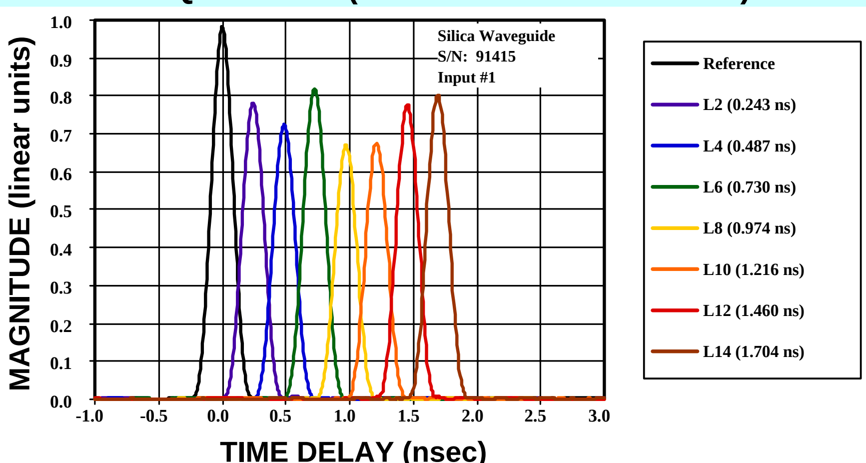
SILICA WAVEGUIDE DELAY-LINE TECHNOLOGY:



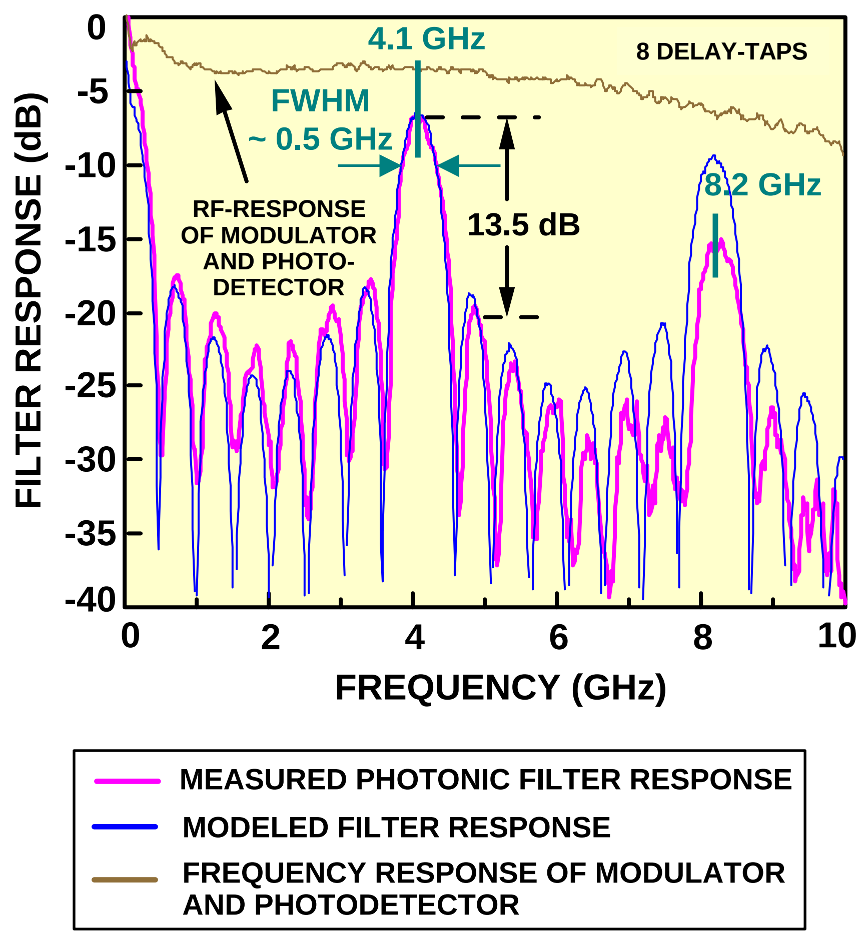
- AREA ~ 6.8 cm x 7 cm
- RIBBON-CONNECTORIZED (SPLICED AS RIBBON)
- LOSS < 0.054 dB/cm



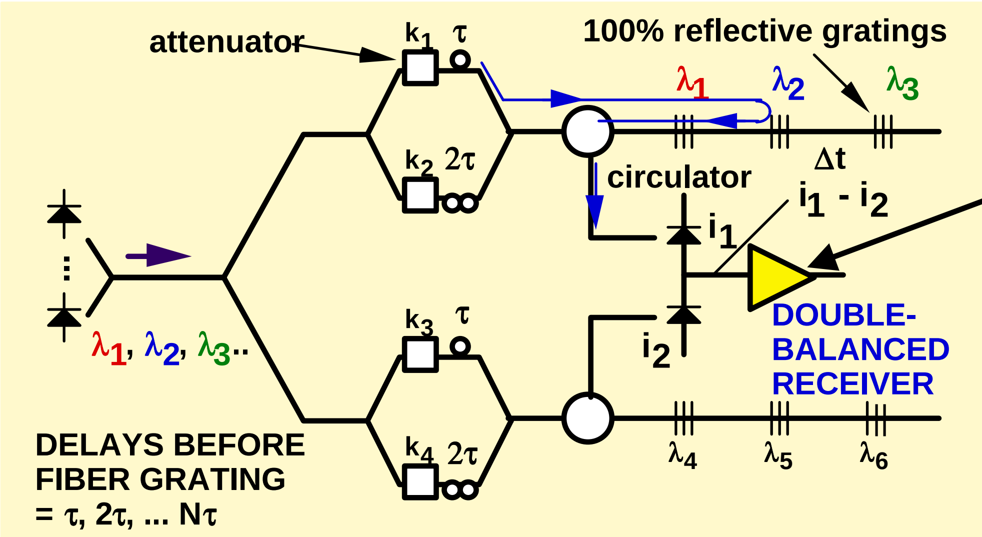
TIME-DELAY MEASURED VIA PULSE RESPONSES: SYNTHESIZED FROM THE FREQ. RESPONSE OF 800 FREQUENCIES (FROM 45 MHz TO 10 GHz):



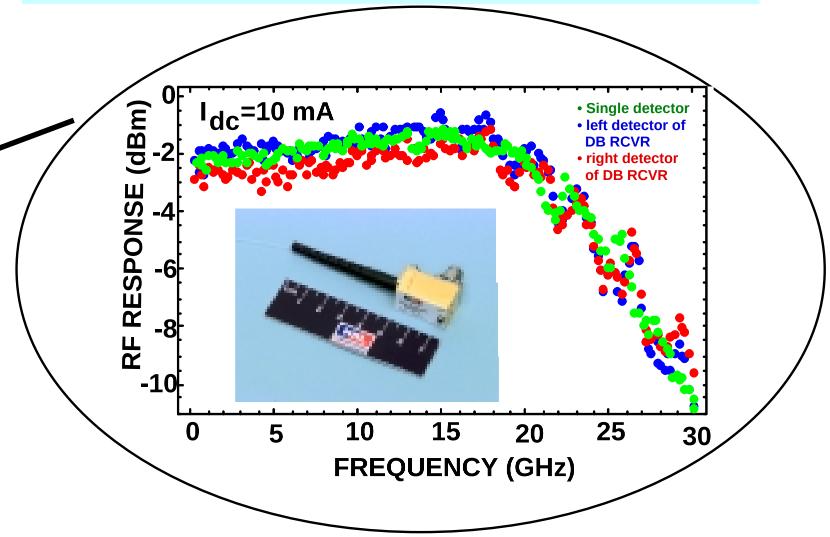
MEASURED AND MODELED FILTER RESPONSE:

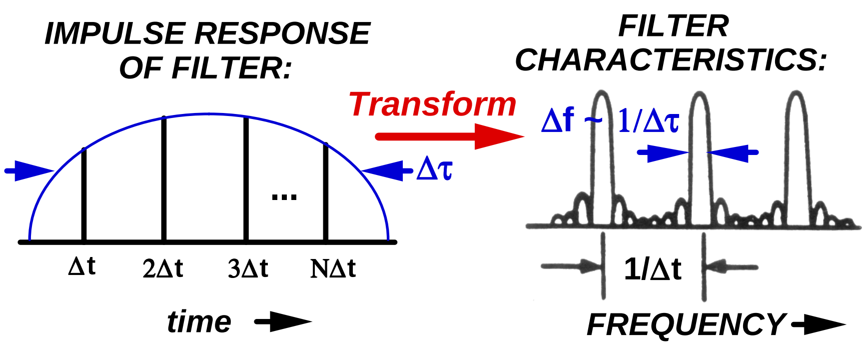


HIGH-Q MICROWAVE FILTERS BASED ON TAPPED DELAY-LINES IMPLEMENTED WITH WDM TECHNOLOGY



20 GHz HRL DOUBLE-BALANCED RECEIVER:





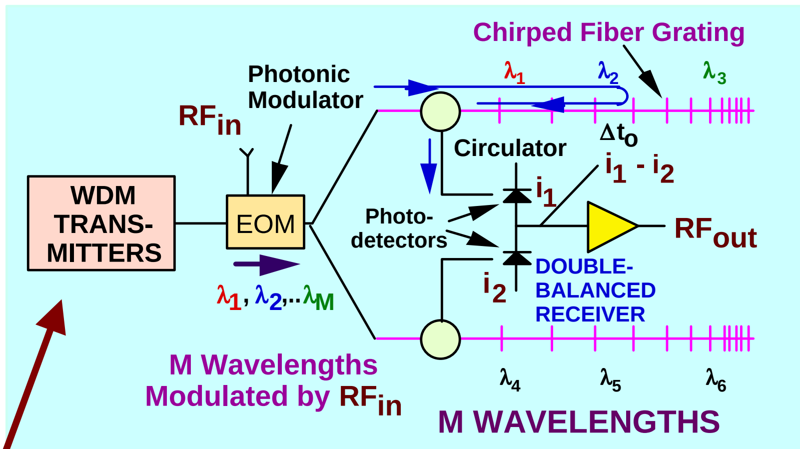
- **FREQUENCY SPACING IS 1/Δt**
- **FILTER Q (=f_c/Δf) INCREASES WITH K, THE NUMBER OF TAPS.**

FEATURES OF WDM-BASED RF-FILTER:

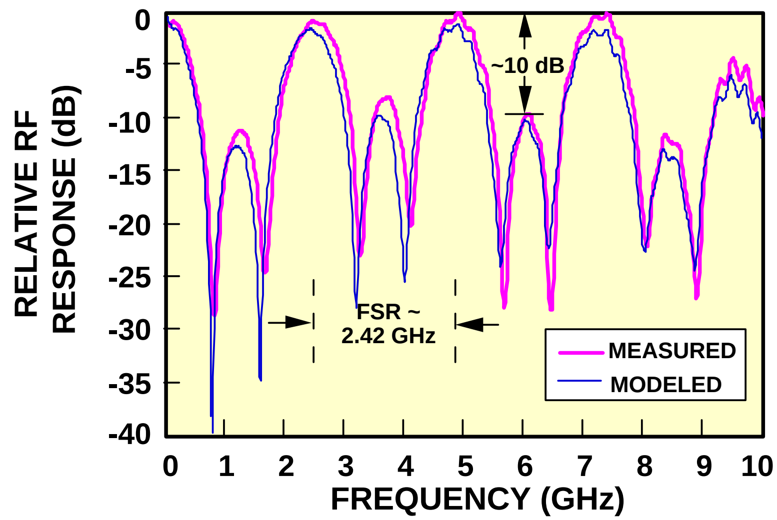
- **USING M MULTIPLEXED WDM LASERS (WITH N DELAY-LINES), THE NUMBER OF TAPS (K) GOES UP AS K = M x N => HIGH Q FILTERS**
- **USING DOUBLE-BALANCED RCVR => FILTER SYNTHESIS WITH +ve & -ve COE.**
- **THE CENTER FREQUENCY AND PASS-BAND OF THE FILTER CAN BE RECONFIGURED AGILELY VIA λ-TUNING.**

PHOTONIC-BASED RF-FILTER USING CHIRPED FIBER GRATING AND HRL WDM TRANSMITTERS

FIR FILTER USING WDM LASER SOURCES AND CHIRPED FIBER GRATINGS (FG):

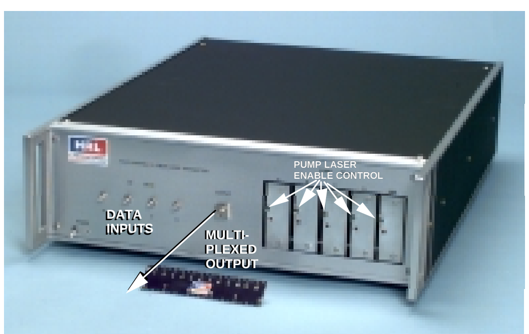


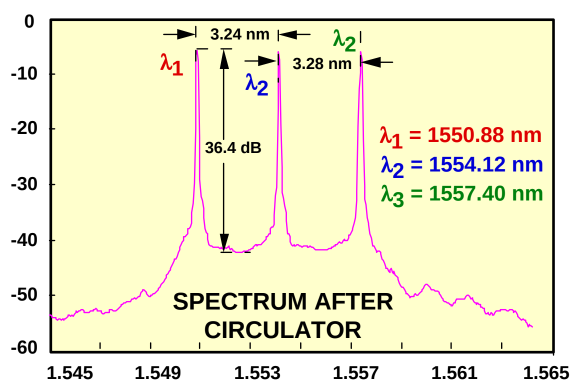
MEASURED AND MODELED RF-RESPONSE OF FILTER:



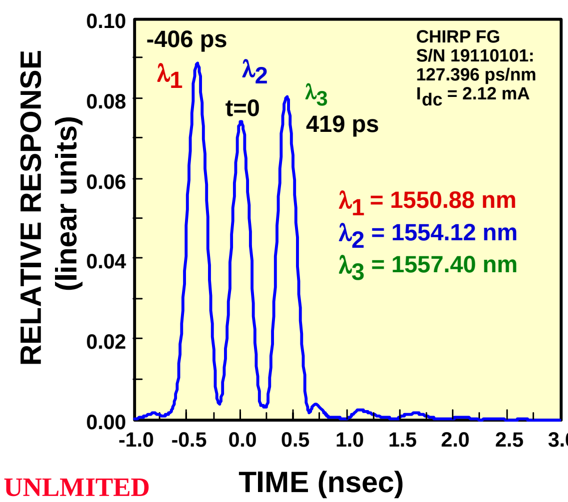
HRL WDM Er-FIBERLASER TRANSMITTER

- U.S. PATENT 6,005,877 (issued 12/21/99)



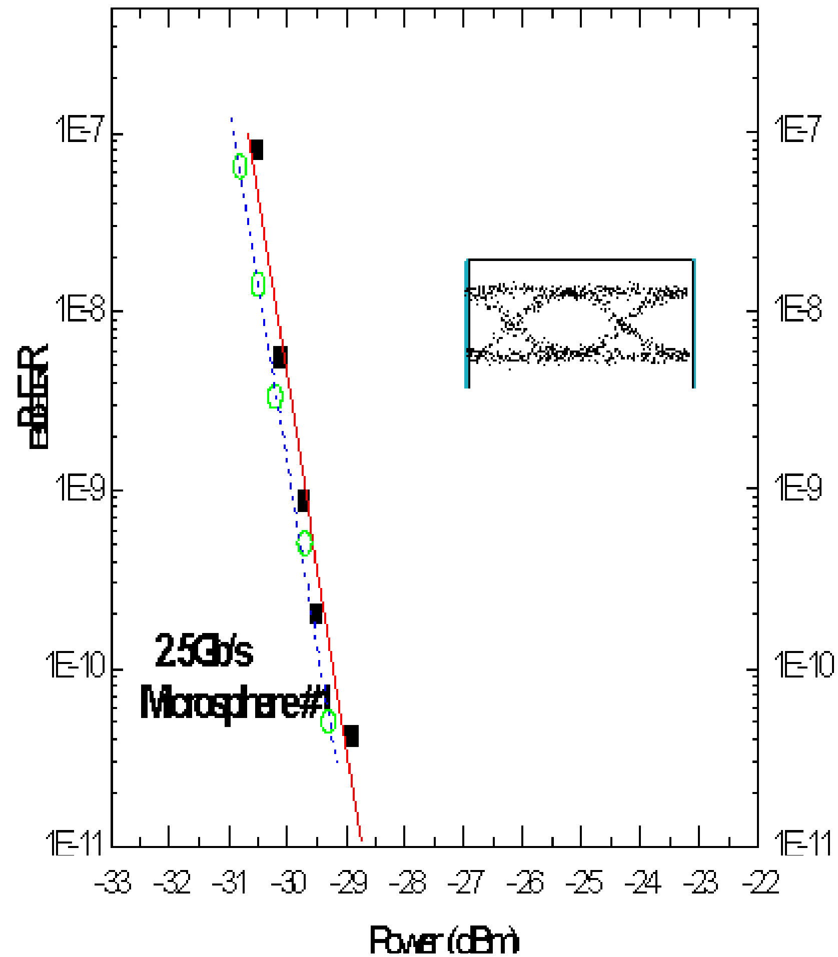


FILTER IMPULSE RESPONSE:



LABORATORIES

HIGH-Q MICROSPHERE RESONATORS: WDM WAVELENGTH ADD-DROP APPLICATIONS



- **Insertion Loss = 0.1 dB**
- **Drop Extinction > 25 dB**
- **Drop Loss < 0.5 dB**
- **Q of 10^4 - 10^6**

(For Q=10^5, Δf ~ 3 GHz)

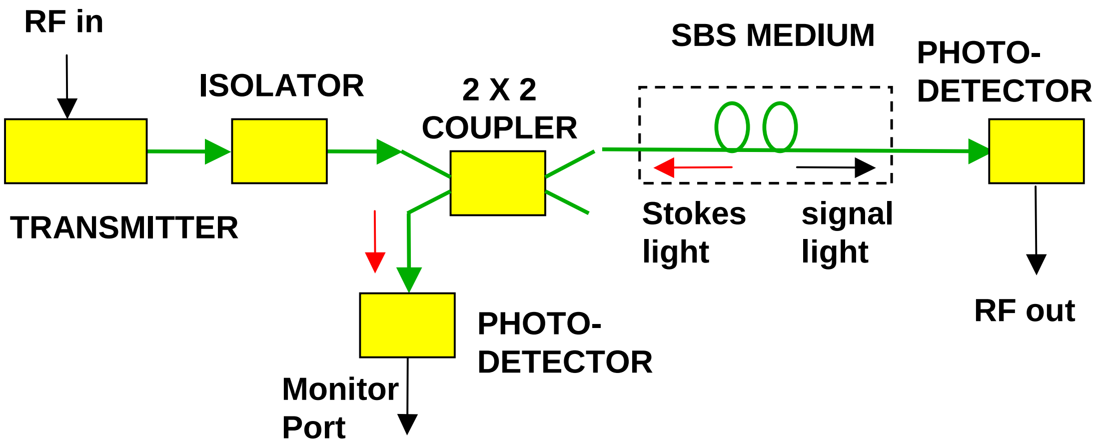
Vahala group

OBJECTIVES:

- **Realize this function with Q > 10^8 (Δf ~ 3 MHz).**
- **Reduce the spectral complexity (resonance degeneracy caused by fabrication eccentricity in micro-resonator) of system.**
- **Achieve a 2-port portable test device and deliver prototype to HRL for Analog Signal Processing applications**

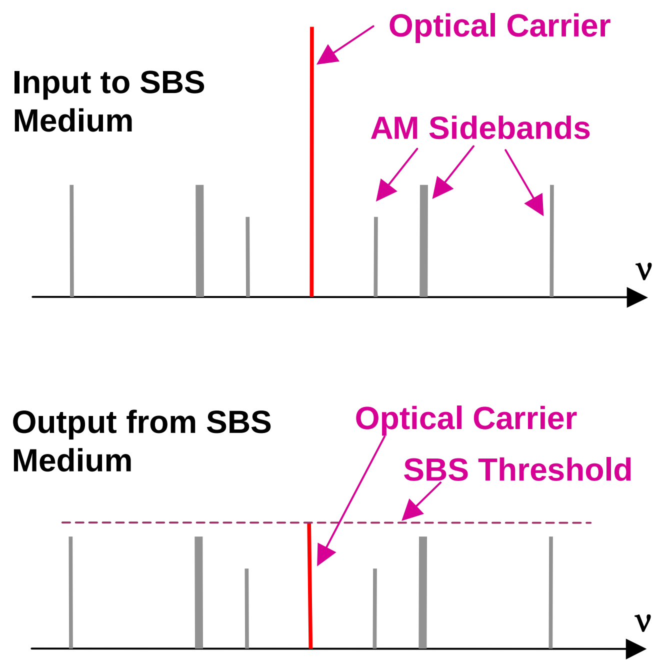
Vahala group

STIMULATED BRILLOUIN SCATTERING FOR IMPROVEMENT OF OPTICAL MODULATION DEPTH



Williams and Esner, Electronics Letters, vol. 30, pp. 1965-1966 (1994)

- SBS in optical fiber limits forward optical power to being below some threshold value
- SBS Threshold depends on length and type of fiber, and can be approximately 5-10 mW for 25 km
- Narrow SBS linewidth means even fairly low-frequency signals are preserved when optical carrier is attenuated
- HRL will investigate ways to apply the SBS effect with shorter fiber lengths



PROGRAM OBJECTIVES AND TASKS FOR PHASE I

TASK 1: PHOTONIC FILTER DEVELOPMENT

- SYSTEM ANALYSIS FOR ESM PULSE DETECTION

TASK 2: PULSE COMPRESSION OF MULTI-LINE LPI WAVEFORM

TASK 3: ADVANCED FREQUENCY CHANNELIZATION COMPONENTS AND PBG DIRECTIONAL COUPLER DEVELOPMENT

- EVALUATE HIGH-Q MICRO-RESONATOR FOR RF-PHOTONIC SIGNAL PROCESSING

TASK 4: SIGNAL PROCESSING DEMONSTRATIONS:

- SYSTEM ANALYSIS OF MULTI-LINE RECEIVER
- USE OF STIMULATED BRILLOUIN SCATTERING (SBS) FOR SIGNAL PROCESSING IN LPI SYSTEM

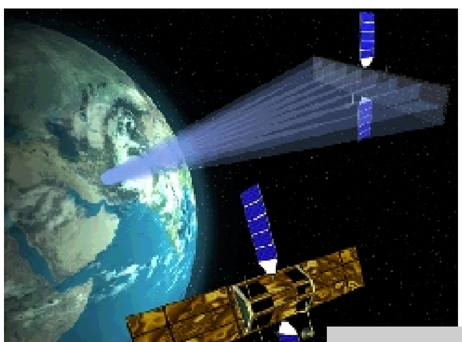
Surveillance and Reconnaissance Systems (El Segundo,CA)

Raytheon

SBIRS-Low

MODIS

U-2



Discoverer II

Global Hawk

P-3

Raptor

SeaVue

E-2C

Raytheon systems capabilities help HRL to serve DARPA's mission goals

• HRL is supported in the DARPA AOSP program by the Advanced Sensor Programs (ASP) product line of Raytheon Company

• As part of the Surveillance and Reconnaissance organization, ASP is active in the development and applications of photonics in evolving multifunction systems

• ASP personnel include professional photonic scientists and engineers with extensive experience in design and production of devices and subsystems

• ASP and Raytheon National Systems (C3I) cooperate to bring both ESM and radar systems experience to advance the goals of AOSP

• This system experience assists HRL to understand how increased functionality due to photonic technologies will benefit users, and to establish meaningful requirements

ASP support activities emphasize requirements and system analysis

• The HRL/Raytheon AOSP program is centered on the wideband frequency agile spread spectrum photonic waveform generator

• ASP's tasks in AOSP are related to system analysis, such as

- Requirements for the multiline RF comb waveform
- Stability and phase noise issues
- Implications of correlated phase noise
- Pulse compression techniques (FM/phase encoding)
- Methods for capturing the comb energy on receive
- Matched filters and correlation receivers